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(54) **ABSOLUTE SENSITIVITY OF A MEMS MICROPHONE WITH CAPACITIVE AND PIEZOELECTRIC ELECTRODES**

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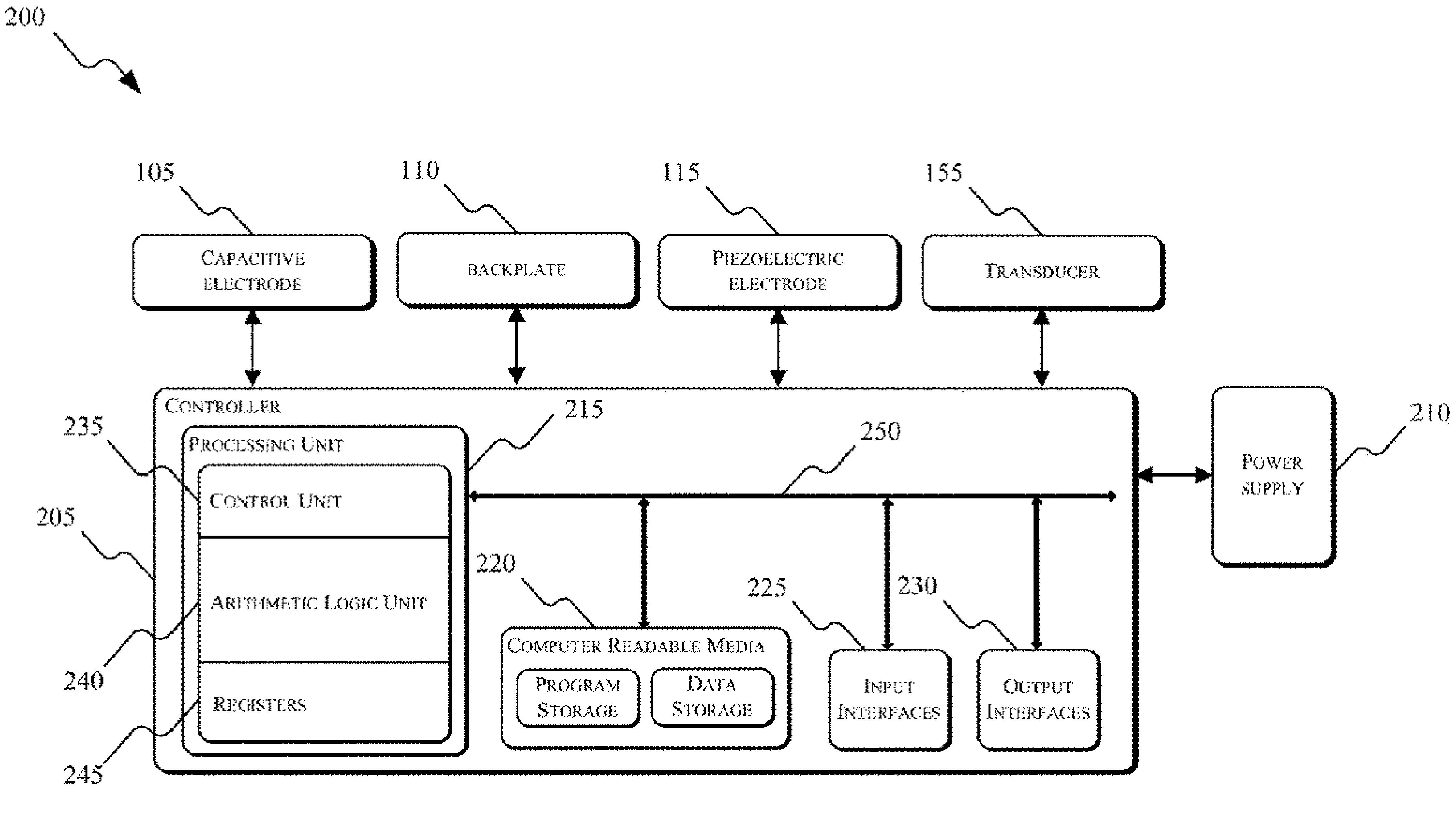
(57) **ABSTRACT**

Microphone systems and methods of determining absolute sensitivities of a MEMS microphone. The microphone system includes a speaker, a MEMS microphone, and a controller. The speaker is configured to generate an acoustic pressure. The MEMS microphone includes a capacitive electrode, a piezoelectric electrode, and a backplate. The capacitive electrode is configured to generate a first capacitive response based on the acoustic pressure and generate a first mechanical pressure based on a capacitive control signal. The piezoelectric electrode is coupled to the capacitive electrode. The piezoelectric electrode is configured to generate a first piezoelectric response signal based on the acoustic pressure and generate a second piezoelectric response signal based on the first mechanical pressure. The controller is configured to generate the capacitive control signal and determine an absolute sensitivity of the capacitive electrode based on the first capacitive response, the first piezoelectric response signal, and the second piezoelectric response signal.

17 Claims, 6 Drawing Sheets



(51) **Int. Cl.**

H04R 23/02	(2006.01)
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(58) **Field of Classification Search**

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See application file for complete search history.

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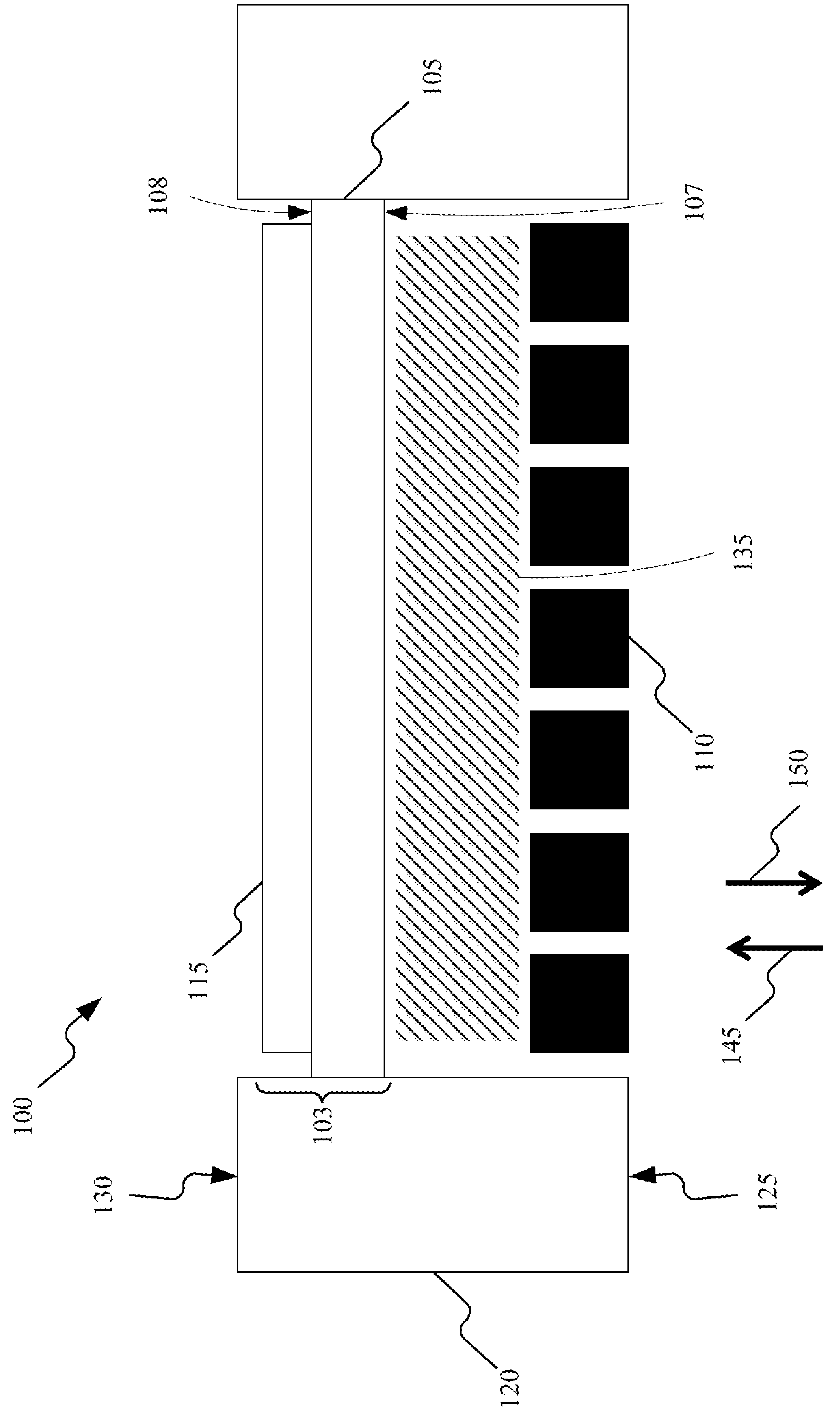


FIG. 1

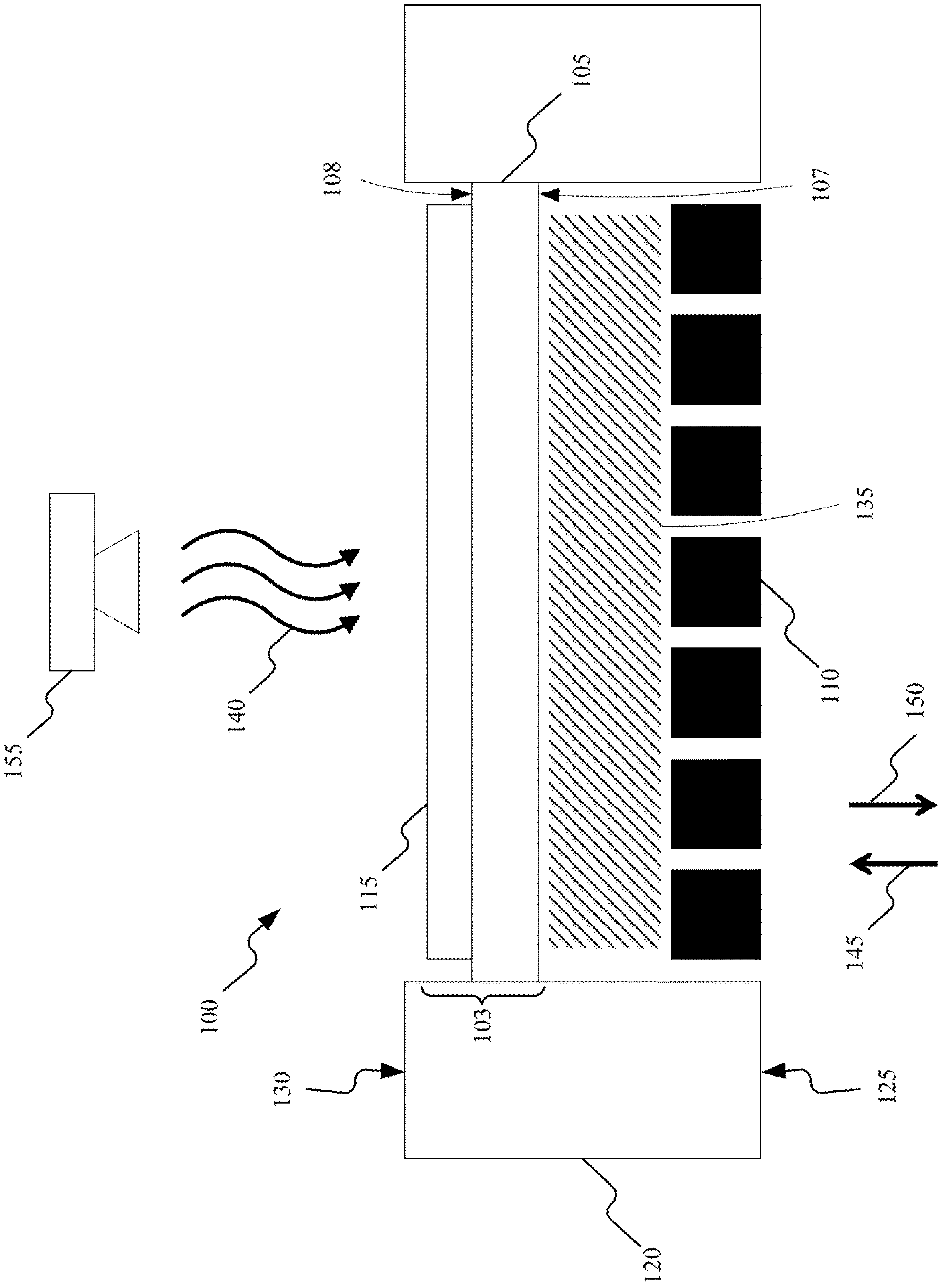


FIG. 2

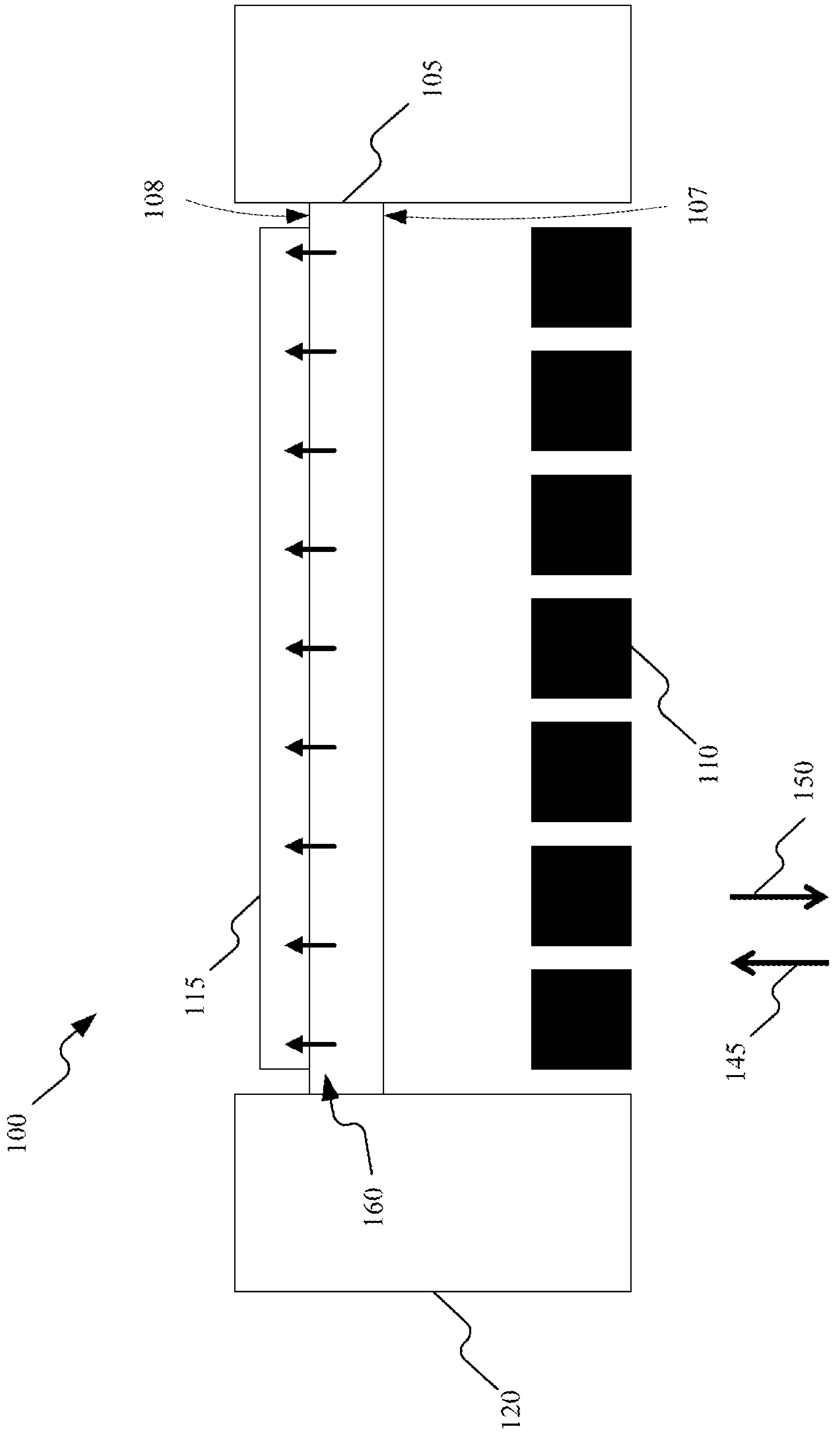


FIG. 3

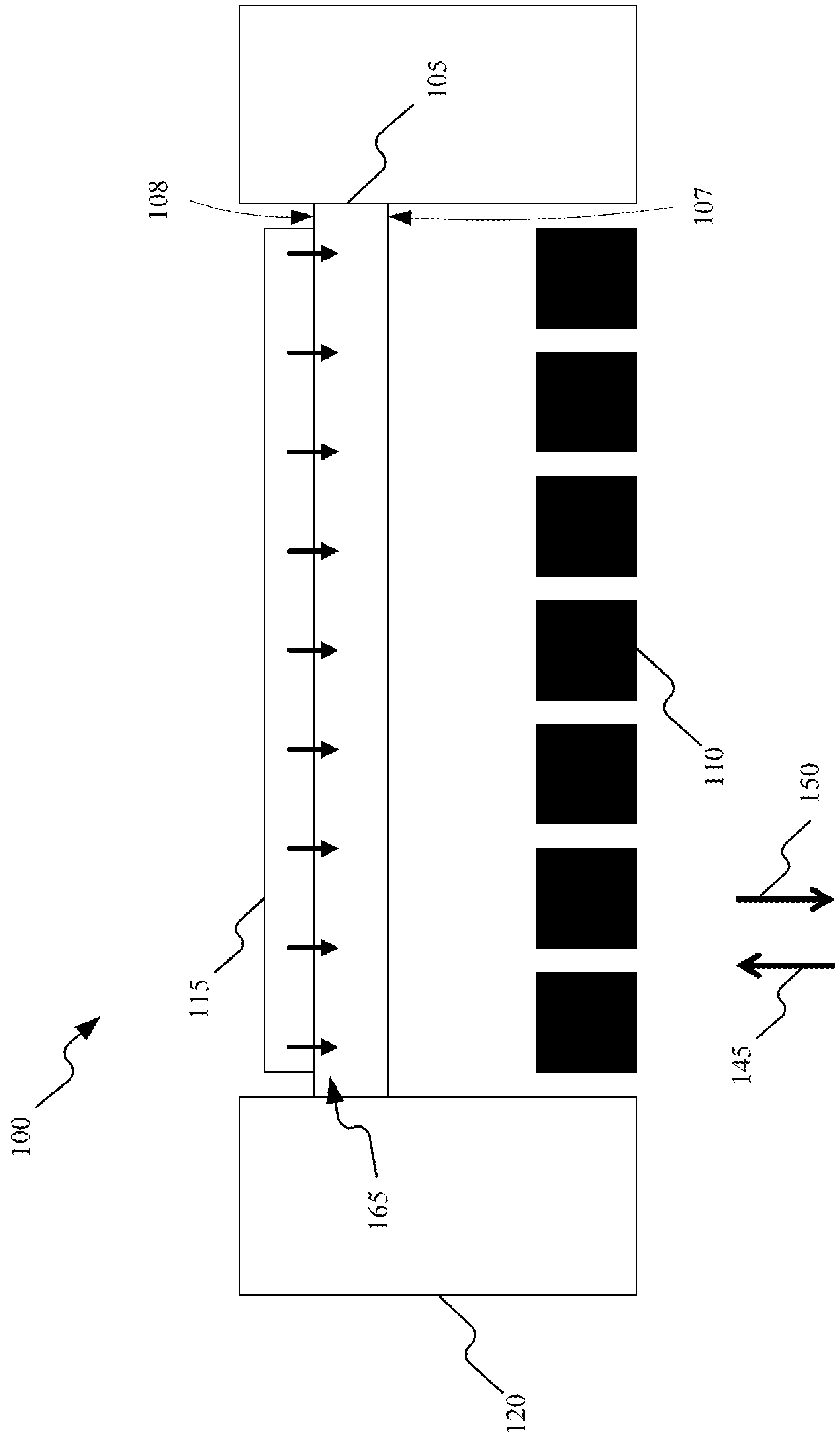


FIG. 4

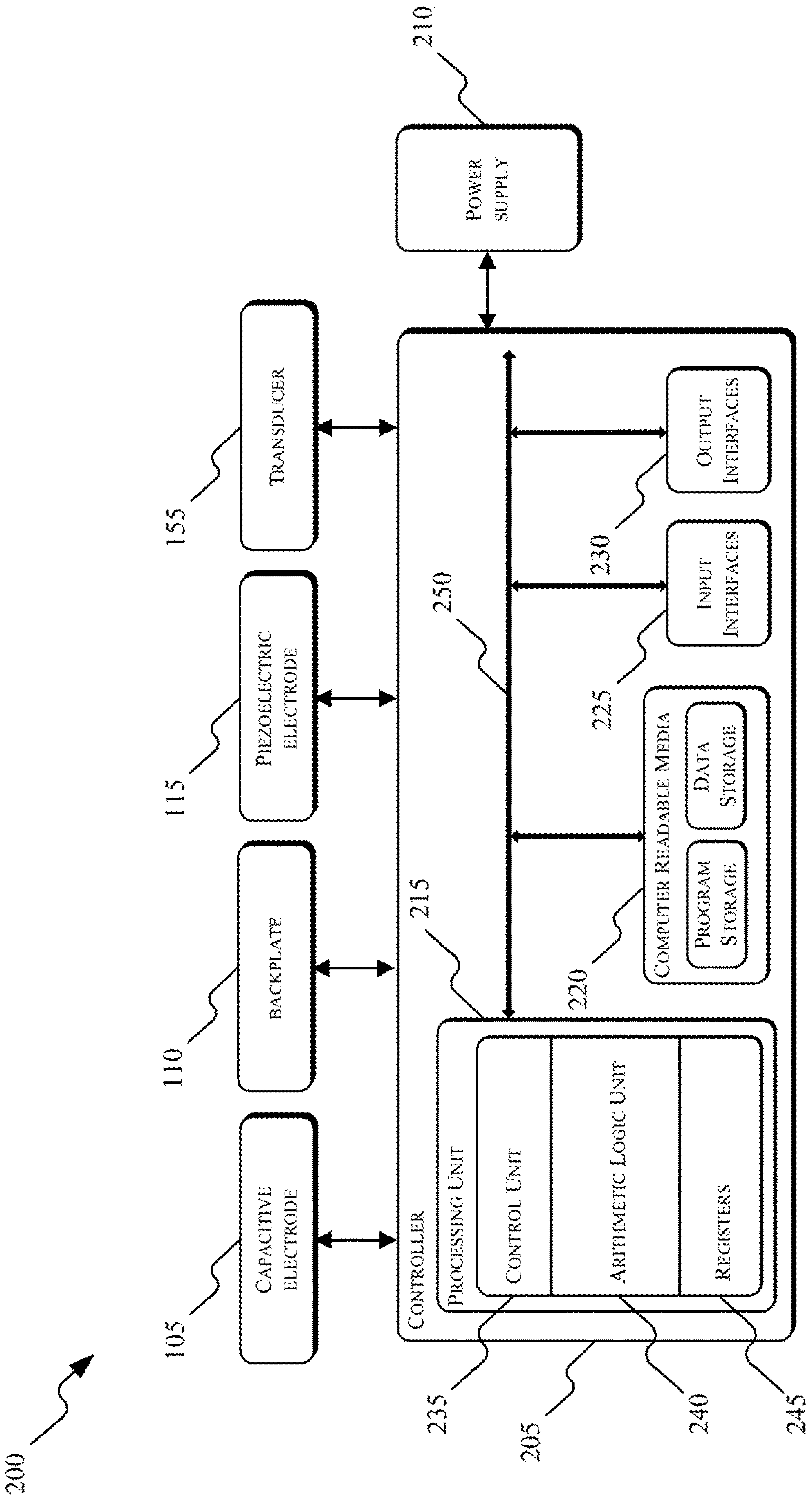
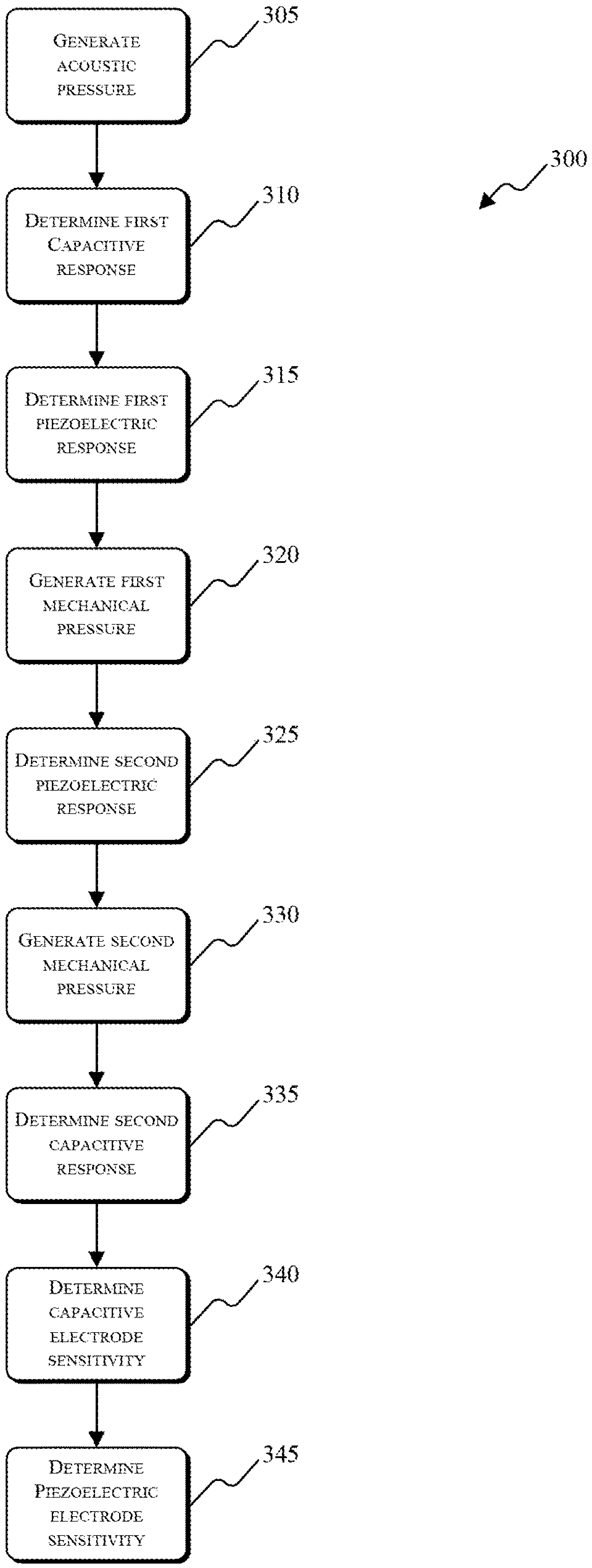

200
105
Capacitive electrode
110
Backplate
115
Piezoelectric electrode
155
Transducer
210
Power supply
Controller
Processing Unit
Control Unit
Arithmetic Logic Unit
Registers
215
250
220
Computer Readable Media
Program Storage
Data Storage
225
Input Interfaces
230
Output Interfaces
205
235
240
245

FIG. 5

FIG. 6


305
GENERATE ACOUSTIC PRESSURE
310
DETERMINE FIRST CAPACITIVE RESPONSE
315
DETERMINE FIRST PIEZOELECTRIC RESPONSE
320
GENERATE FIRST MECHANICAL PRESSURE
325
DETERMINE SECOND PIEZOELECTRIC RESPONSE
330
GENERATE SECOND MECHANICAL PRESSURE
335
DETERMINE SECOND CAPACITIVE RESPONSE
340
DETERMINE CAPACITIVE ELECTRODE SENSITIVITY
345
DETERMINE PIEZOELECTRIC ELECTRODE SENSITIVITY
300

ABSOLUTE SENSITIVITY OF A MEMS MICROPHONE WITH CAPACITIVE AND PIEZOELECTRIC ELECTRODES

RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 14/970,175, entitled "ABSOLUTE SENSITIVITY OF A MEMS MICROPHONE WITH CAPACITIVE AND PIEZOELECTRIC ELECTRODES" filed Dec. 15, 2015, which is incorporated herein by reference in its entirety.

BACKGROUND

Embodiments of the disclosure relate to micro-electro-mechanical system (MEMS) microphones with both capacitive and piezoelectric electrodes.

The absolute sensitivity of an electrode in a MEMS microphone is the electrical response of the electrode's output to a given standard acoustic input. Allowable product variation of absolute sensitivities in MEMS microphones is, in general, decreasing. In addition, allowable testing time to determine the absolute sensitivities in MEMS microphones is also decreasing.

SUMMARY

Coupling a piezoelectric electrode to a capacitive electrode in a MEMS microphone adds a second reciprocal sensor which can be used to determine the absolute sensitivity.

One embodiment provides a microphone system. In one embodiment, the microphone system includes a speaker, a MEMS microphone, and a controller. The speaker is configured to generate an acoustic pressure. The MEMS microphone includes a capacitive electrode, a piezoelectric electrode, and a backplate. The capacitive electrode is configured to generate a first capacitive response based on the acoustic pressure. The capacitive electrode is also configured to generate a first mechanical pressure based on a capacitive control signal. The piezoelectric electrode is coupled to the capacitive electrode. The piezoelectric electrode is configured to generate a first piezoelectric response signal based on the acoustic pressure. The piezoelectric electrode is also configured to generate a second piezoelectric response signal based on the first mechanical pressure. The controller is configured to generate the capacitive control signal. The controller is also configured to determine an absolute sensitivity of the capacitive electrode based on the first capacitive response, the first piezoelectric response signal, and the second piezoelectric response signal.

Another embodiment provides a method of determining absolute sensitivities of a MEMS microphone. In one embodiment, the MEMS microphone includes a capacitive electrode, a piezoelectric electrode, and a backplate. The piezoelectric electrode is coupled to the capacitive electrode. The method includes generating acoustic pressure with a speaker. The method also includes generating a first capacitive response with the capacitive electrode based on the acoustic pressure. The method further includes generating a first piezoelectric response with the piezoelectric electrode based on the acoustic pressure. The method also includes generating a capacitive control signal with a controller. The method further includes generating a first mechanical pressure with the capacitive electrode based on the capacitive control signal. The method also includes generating a second piezoelectric response with the piezoelectric electrode based on the first mechanical pressure. The method further includes determining an absolute sensitivity of the capacitive electrode with the controller based in part on the first capacitive response, the first piezoelectric response, and the second piezoelectric response.

Yet another embodiment provides a microphone system. In one embodiment, the microphone system includes a speaker, a MEMS microphone, and a controller. The speaker is configured to generate an acoustic pressure. The MEMS microphone includes movable membrane and a backplate. The movable membrane includes a capacitive electrode and a piezoelectric electrode. The capacitive electrode is configured to generate a first capacitive response based on the acoustic pressure. The capacitive electrode is also configured to generate a first mechanical pressure based on a capacitive control signal. The piezoelectric electrode is configured to generate a first piezoelectric response signal based on the acoustic pressure. The piezoelectric electrode is also configured to generate a second piezoelectric response signal based on the first mechanical pressure. The backplate is positioned on the capacitive electrode. The controller is configured to generate the capacitive control signal. The controller is also configured to determine an absolute sensitivity of the capacitive electrode based on the first capacitive response, the first piezoelectric response signal, and the second piezoelectric response signal.

Still another embodiment provides a microphone system. In one embodiment, the microphone system includes a speaker, a MEMS microphone, and a controller. The speaker is configured to generate an acoustic pressure based on a speaker control signal. The MEMS microphone includes a capacitive electrode, a backplate, and a piezoelectric electrode. The capacitive electrode is configured such that the acoustic pressure causes a first movement of the capacitive electrode. The capacitive electrode is also configured to generate a first mechanical pressure based on a capacitive control signal. The backplate is positioned on a first side of the capacitive electrode. The piezoelectric electrode is coupled to the capacitive electrode. The piezoelectric electrode is configured to generate a first piezoelectric response signal based on the acoustic pressure. The piezoelectric electrode is further configured to generate a second piezoelectric response signal based on the first mechanical pressure. The controller is coupled to the speaker, the capacitive electrode, the backplate, and the piezoelectric electrode. The controller is configured to generate the speaker control signal. The controller is also configured to determine a first capacitive response based on the first movement of the capacitive electrode. The controller is further configured to generate the capacitive control signal. The controller is also configured to determine an absolute sensitivity of the capacitive electrode based on the first capacitive response, the first piezoelectric response signal, and the second piezoelectric response signal.

Another embodiment provides a method of determining absolute sensitivities of a MEMS microphone. In one embodiment, the MEMS microphone includes a capacitive electrode, a backplate, and a piezoelectric electrode. The piezoelectric electrode is coupled to the capacitive electrode. The method includes generating, by a speaker, an acoustic pressure based on a speaker control signal. The method further includes determining, by a controller, a first capacitive response of the capacitive electrode in response to the acoustic pressure. The method also includes determining, by the controller, a first piezoelectric response of the piezoelectric electrode in response to the acoustic pressure. The method further includes, generating, by the capacitive electrode, a first mechanical pressure based on a capacitive control signal. The method also includes determining, by the controller, a second piezoelectric response of the piezoelectric electrode in response to the first mechanical pressure. The method further includes determining, by the controller, an absolute sensitivity of the capacitive electrode based on the first capacitive response, the first piezoelectric response, and the second piezoelectric response.

Yet another embodiment provides a microphone system. In one embodiment, the microphone system includes a speaker, a MEMS microphone, and a controller. The speaker is configured to generate an acoustic pressure based on a speaker control signal. The MEMS microphone includes a movable membrane and a backplate. The movable membrane includes a piezoelectric electrode and a capacitive electrode. The capacitive electrode is configured such that the acoustic pressure causes a first movement of the capacitive electrode. The capacitive electrode is also configured to generate a first mechanical pressure based on a capacitive control signal. The piezoelectric electrode is configured to generate a first piezoelectric response signal based on the acoustic pressure. The piezoelectric electrode is further configured to generate a second piezoelectric response signal based on the first mechanical pressure. The backplate is positioned on the capacitive electrode. The controller is coupled to the speaker, the capacitive electrode, the backplate, and the piezoelectric electrode. The controller is configured to generate the speaker control signal. The controller is also configured to determine a first capacitive response based on the first movement of the capacitive electrode. The controller is further configured to generate the capacitive control signal. The controller is also configured to determine an absolute sensitivity of the capacitive electrode based on the first capacitive response, the first piezoelectric response signal, and the second piezoelectric response signal.

Other aspects of the disclosure will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a cross-sectional view of a MEMS microphone, in accordance with some embodiments.

FIG. **2** is a cross-sectional view of a MEMS microphone and a speaker, in accordance with some embodiments.

FIG. **3** is a cross-sectional view of a MEMS microphone, in accordance with some embodiments.

FIG. **4** is a cross-sectional view of a MEMS microphone, in accordance with some embodiments.

FIG. **5** is a schematic diagram of a microphone system, in accordance with some embodiments.

FIG. **6** is a flowchart of determining absolute sensitivities of a MEMS microphone, in accordance with some embodiments.

DETAILED DESCRIPTION

Before any embodiments of the invention are explained in detail, it is to be understood that the disclosure is not limited in its application to the details of construction and the arrangement of components set forth in the following description or illustrated in the following drawings. The disclosure is capable of other embodiments and of being practiced or of being carried out in various ways.

Also, it is to be understood that the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of “including,” “comprising” or “having” and variations thereof herein is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. The terms “mounted,” “connected” and “coupled” are used broadly and encompass both direct and indirect mounting, connecting and coupling. Further, “connected” and “coupled” are not restricted to physical or mechanical connections or couplings, and can include electrical connections or couplings, whether direct or indirect. Also, electronic communications and notifications may be performed using other known means including direct connections, wireless connections, etc. In addition, the terms “positive” and “negative” are used to distinguish one entity or action from another entity or action without necessarily requiring or implying any such attribute of the entity or action.

It should also be noted that a plurality of hardware and software based devices, as well as a plurality of other structural components may be utilized to implement the disclosure. Furthermore, and as described in subsequent paragraphs, the specific configurations illustrated in the drawings are intended to exemplify embodiments of the disclosure. Alternative configurations are possible.

In some embodiments, a MEMS microphone **100** includes, among other components, a movable membrane **103**. In the example illustrated, the movable membrane **103** includes a capacitive electrode **105** having a first side **107** and a second side **108**. The capacitive electrode **105** is also a movable membrane. The movable membrane **103** also includes a piezoelectric electrode **115**. A fixed member (i.e., a backplate **110**) and a barrier **120** are provided in the MEMS microphone **100**. The second side **108** of the capacitive electrode **105** is opposite from the first side **107** of the capacitive electrode **105**. In some embodiments, the backplate **110** is positioned on the first side **107** of the capacitive electrode **105**, as illustrated in FIGS. **1-4**. In other embodiments, the backplate **110** is positioned on the second side **108** of the capacitive electrode **105**. The barrier **120** isolates a first side **125** and a second side **130** of the MEMS microphone **100**.

In some embodiments, the capacitive electrode **105** is kept at a reference voltage and a bias voltage is applied to the backplate **110** to generate an electric sense field **135** between the capacitive electrode **105** and the backplate **110**. In other embodiments, the backplate **110** is kept at a reference voltage and a bias voltage is applied to the capacitive electrode **105** to generate the electric sense field **135** between the capacitive electrode **105** and the backplate **110**. In some embodiments, the reference voltage is a ground reference voltage (i.e., approximately 0 Volts). In other embodiments, the reference voltage is a non-zero voltage. The electric sense field **135** is illustrated in FIGS. **1** and **2** as a plurality of diagonal lines. Deflection of the capacitive electrode **105** in the directions of arrow **145** and **150** modulates the electric sense field **135** between the capacitive electrode **105** and the backplate **110**. A voltage difference between the capacitive electrode **105** and the backplate **110** varies based on the electric sense field **135**.

As illustrated in FIG. **2**, acoustic pressure **140** acting on the second side **108** of the capacitive electrode **105** causes a first movement (e.g., deflection) of the capacitive electrode **105** in the direction of arrow **150**. The acoustic pressure **140** is illustrated in FIG. **2** as a plurality of wavy arrows in the direction of arrow **150**. The acoustic pressure **140** is generated by a transducer **155**. The transducer **155** may be a receiver, a speaker, and the like. Although one speaker is illustrated, more than one speaker may be used, depending on the application. The transducer **155** generates the acoustic pressure **140** based on a received speaker control signal. The first movement of the capacitive electrode **105** modulates the electric sense field **135** between the capacitive electrode **105** and the backplate **110**. A first voltage difference between the capacitive electrode **105** and the backplate **110** varies based on the first movement of the capacitive electrode **105**.

In some embodiments, a capacitive control signal is applied to the capacitive electrode **105**. The capacitive control signal causes the capacitive electrode **105** to generate a first mechanical pressure **160**, as illustrated in FIG. **3**. The first mechanical pressure **160** is illustrated in FIG. **3** as a plurality of straight arrows in the direction of arrow **145**. In some embodiments, the capacitive control signal is a current signal.

In one embodiment, the piezoelectric electrode **115** is a layer or material that uses the piezoelectric effect to measure changes in pressure or force by converting them to an electrical charge. In some embodiments, the piezoelectric electrode **115** includes aluminum nitride (AlN). In other embodiments, the piezoelectric electrode **115** includes zinc oxide (ZnO). In other embodiments, the piezoelectric electrode **115** includes lead zirconate titanate (PZT). The piezoelectric electrode **115** generates piezoelectric response signals in response to pressure (e.g., acoustic, mechanical) being applied to the piezoelectric electrode **115**. In some embodiments, the piezoelectric electrode **115** is formed on the capacitive electrode **105** by a suitable deposition technique (e.g., atomic layer deposition), and defines a fabricated piezoelectric membrane.

The piezoelectric electrode **115** is coupled to the capacitive electrode **105**. In some embodiments, the piezoelectric electrode **115** is coupled to the second side **108** of the capacitive electrode **105**, as illustrated in FIGS. **1-4**. In other embodiments, the piezoelectric electrode **115** is coupled to the first side **107** of the capacitive electrode **105**. In some embodiments, the piezoelectric electrode **115** is formed on either side of the capacitive electrode **105** by a deposition technique.

The piezoelectric electrode **115** is configured to receive the acoustic pressure **140**. The piezoelectric electrode **115** generates a first piezoelectric response signal in response to the acoustic pressure **140**. The piezoelectric electrode **115** generates a second piezoelectric response signal in response to the first mechanical pressure **160** exerted by the capacitive electrode **105**. In some embodiments, the first and second piezoelectric response signals are voltage signals.

In some embodiments, a piezoelectric control signal is applied to the piezoelectric electrode **115**. The piezoelectric control signal causes a shape of the piezoelectric electrode **115** to change. The shape change results in the piezoelectric electrode **115** generating a second mechanical pressure **165**, as illustrated in FIG. **4**. The second mechanical pressure **165** is illustrated in FIG. **4** as a plurality of straight arrows in the direction of arrow **150**. In some embodiments, the piezoelectric control signal is a current signal.

The second mechanical pressure **165** generated by the shape change of the piezoelectric electrode **115** in turn causes a second movement of the capacitive electrode **105**. Similar to the first movement, the second movement of the capacitive electrode **105** modulates the electric sense field **135** between the capacitive electrode **105** and the backplate **110**. A second voltage difference between the capacitive electrode **105** and the backplate **110** varies based on the second movement of the capacitive electrode **105**.

In some embodiments, the piezoelectric material is deposited on the second side **108** of the movable membrane so as to form the piezoelectric electrode **115**. The first side **107** of the movable membrane defines the capacitive electrode **105**. The piezoelectric electrode **115** generates the first response signal in response to the acoustic pressure **140**. The piezoelectric electrode **115** generates the second piezoelectric signal in response to the first mechanical pressure **160** exerted by the capacitive electrode **105**. The second mechanical pressure **165** generated by the shape change of the piezoelectric electrode **115**, in turn, causes a second movement of the capacitive electrode **105**. Similar to the first movement, the second movement of the capacitive electrode **105** modulates the electric sense field **135** between the capacitive electrode **105** and the backplate **110**. A second voltage difference between the capacitive electrode **105** and the backplate **110** varies based on the second movement of the capacitive electrode **105**.

In some embodiments, a microphone system **200** includes, among other components, the MEMS microphone **100**, the transducer **155**, a controller **205**, and a power supply **210**, as illustrated in FIG. **5**.

In some embodiments, the controller **205** includes a plurality of electrical and electronic components that provide power, operational control, and protection to the components and modules within the controller **205**, the MEMS microphone **100**, the transducer **155**, and/or the microphone system **200**. For example, the controller **205** includes, among other components, a processing unit **215** (e.g., a microprocessor, a microcontroller, or another suitable programmable device), a memory or computer readable media **220**, input interfaces **225**, and output interfaces **230**. The processing unit **215** includes, among other components, a control unit **235**, an arithmetic logic unit (ALU) **240**, and a plurality of registers **245** (shown as a group of registers in FIG. **5**), and is implemented using a known computer architecture, such as a modified Harvard architecture, a von Neumann architecture, etc. The processing unit **215**, the computer readable media **220**, the input interfaces **225**, and the output interfaces **230**, as well as the various modules connected to the controller **205** are connected by one or more control and/or data buses (e.g., common bus **250**). The control and/or data buses are shown generally in FIG. **5** for illustrative purposes. The use of one or more control and/or data buses for the interconnection between and communication among the various modules and components would be known to a person skilled in the art in view of the invention described herein. In some embodiments, the controller **205** is implemented partially or entirely on a semiconductor chip, is a field-programmable gate array (FPGA), is an application specific integrated circuit (ASIC), or is a similar device.

The computer readable media **220** includes, for example, a program storage area and a data storage area. The program storage area and the data storage area can include combinations of different types of memory, such as read-only memory (ROM), random access memory (RAM) (e.g., dynamic RAM [DRAM], synchronous DRAM [SDRAM], etc.), electrically erasable programmable read-only memory (EEPROM), flash memory, a hard disk, an SD card, or other suitable magnetic, optical, physical, or electronic memory devices or data structures. The processing unit **215** is connected to the computer readable media **220** and executes software instructions that are capable of being stored in a RAM of the computer readable media **220** (e.g., during execution), a ROM of the computer readable media **220** (e.g., on a generally permanent basis), or another nontransitory computer readable medium such as another memory or a disc. Software included in some embodiments of the microphone system **200** can be stored in the computer readable media **220** of the controller **205**. The software includes, for example, firmware, one or more applications, program data, filters, rules, one or more program modules, and other executable instructions. The controller **205** is configured to retrieve from memory and execute, among other things, instructions related to the control processes and methods described herein. In other constructions, the controller **205** includes additional, fewer, or different components.

The controller **205** is coupled to the capacitive electrode **105** and the backplate **110**. As described herein, the acoustic pressure **140** generated by the transducer **155** causes the first movement of the capacitive electrode **105**. The controller **205** determines a first capacitive response of the capacitive electrode **105** in response to the acoustic pressure **140** being applied. The first capacitive response is based on the first movement of the capacitive electrode **105**. In some embodiments, the controller **205** determines the first voltage difference between the capacitive electrode **105** and the backplate **110** caused by the first movement of the capacitive electrode **105**. Further, the controller **205** determines the first capacitive response based on the first voltage difference.

Also, as described herein, the second mechanical pressure **165**, generated by the piezoelectric electrode **115**, causes a second movement of the capacitive electrode **105**. The controller **205** determines a second capacitive response of the capacitive electrode **105** in response to the second mechanical pressure **165** being applied. The second capacitive response is based on the second movement of the capacitive electrode **105**. In some embodiments, the controller **205** determines the second voltage difference between the capacitive electrode **105** and the backplate **110** caused by the second movement of the capacitive electrode **105**. Further, the controller **205** determines the second capacitive response based on the second voltage difference. The controller **205** also generates and applies the capacitive control signal to the capacitive electrode **105**.

The controller **205** is also coupled to the piezoelectric electrode **115**. The controller **205** receives the first and second piezoelectric response signals generated by the piezoelectric electrode **115**. In some embodiments, the controller **205** generates and applies the piezoelectric control signal to the piezoelectric electrode **115**.

The controller **205** is further coupled to the transducer **155**. The controller **205** generates and applies the speaker control signal to the transducer **155**.

The power supply **210** supplies a nominal AC or DC voltage to the controller **205** and/or other components of the microphone system **200**. The power supply **210** is powered by one or more batteries or battery packs. The power supply **210** is also configured to supply lower voltages to operate circuits and components within the microphone system **200**. In some embodiments, the power supply **210** generates, among other things, the speaker control signal, the piezoelectric control signal, and the capacitive control signal. In some embodiments, the power supply **210** is powered by mains power having nominal line voltages between, for example, 100V and 240V AC and frequencies of approximately 50-60 Hz.

In one embodiment, the controller **205** determines absolute sensitivities of the capacitive electrode **105** and the piezoelectric electrode **115** using a reciprocity technique. The reciprocity technique includes a plurality of measurements. A first measurement includes the controller **205** applying the speaker control signal to the transducer **155** and determining the first capacitive response of the capacitive electrode **105**. A second measurement includes the controller **205** applying the speaker control signal to the transducer **155** and determining the first piezoelectric response (e.g., the first piezoelectric response signal) of the piezoelectric electrode **115**. A third measurement includes the controller **205** applying a capacitive control signal to the capacitive electrode **105** and determining the second piezoelectric response (e.g., the second piezoelectric response signal) of the piezoelectric electrode **115**. In some embodiments, a fourth measurement includes the controller **205** applying the piezoelectric control signal to the piezoelectric electrode **115** and determining the second capacitive response of the capacitive electrode **105**.

The first and second measurements can be used with the following equations:

$$V_{C1}=M_C\times P_S \quad (1)$$

wherein,

V_{C1}=first capacitive response of the capacitive electrode **105**,

M_C=absolute sensitivity of the capacitive electrode **105**, and

P_S=acoustic pressure **140** applied to the capacitive electrode **105** by the transducer **155** in response to the speaker control signal.

$$V_{P1}=M_P\times P_S \quad (2)$$

wherein,

V_{P1}=first piezoelectric response of the piezoelectric electrode **115**,

M_P=absolute sensitivity of the piezoelectric electrode **115**, and

P_S=acoustic pressure **140** applied to the piezoelectric electrode **115** by the transducer **155** in response to the speaker control signal.

The same amount of acoustic pressure **140** is applied by the transducer **155** to the capacitive electrode **105** and the piezoelectric electrode **115**. Therefore, equations 1 and 2 can be combined to form the follow equation:

$$M_P=M_C\times(V_{P1}/V_{C1}) \quad (3).$$

The third measurement can be used with following equation:

$$M_P\times M_O=(1/Z_M)\times(V_{P2}/I_C) \quad (4)$$

wherein,

Z_M=mechanical transfer impedance,

V_{P2}=second piezoelectric response of the piezoelectric electrode **115**, and

I_C=capacitive control signal.

The mechanical transfer impedance is a system variable that is determined based on the construction on the MEMS microphone **100**. In some embodiments, the mechanical transfer impedance is substantially equal to one.

Equations 3 and 4 can be combined to form the following equation to determine the absolute sensitivity of the capacitive electrode **105**:

$$(M_C)^2=(V_{C1}/V_{P1})\times(1/Z_M)\times(V_{P2}/I_C) \quad (5).$$

The fourth measurement can be used with the following equation:

$$M_P\times M_O=(1/Z_M)\times(V_{C2}/I_P) \quad (6)$$

wherein,

V_{C2}=second capacitive response of the capacitive electrode **105**, and

I_P=piezoelectric control signal.

Equations 3 and 6 can be combined to form the following equation to determine the absolute sensitivity of the piezoelectric electrode **115**:

$$(M_P)^2=(V_{P1}/V_{C1})\times(1/Z_M)\times(V_{C2}/I_P) \qquad (7).$$

FIG. **6** illustrates a process **300** (or method) for determining the absolute sensitivities of the capacitive electrode **105** and the piezoelectric electrode **115**. Various steps described herein with respect to the process **300** are capable of being executed simultaneously, in parallel, or in an order that differs from the illustrated serial manner of execution. The process **300** may also be capable of being executed using fewer steps than are shown in the illustrated embodiment. As will be explained in greater detail, portions of the process **300** can be implemented in software executed by the controller **205**.

The process **300** begins with the generation of acoustic pressure **140** by the transducer **155** (step **305**). In some embodiments, the transducer **155** generates the acoustic pressure **140** in response to receiving the speaker control signal from the controller **205**. The controller **205** determines the first capacitive response of the capacitive electrode **105** in response to the acoustic pressure **140** (step **310**). The controller **205** also determines the first piezoelectric response of the piezoelectric electrode **115** in response to the acoustic pressure **140** (step **315**).

Next, the capacitive electrode **105** generates the first mechanical pressure **160** (step **320**). In some embodiments, the capacitive electrode **105** generates the first mechanical pressure **160** in response to receiving the capacitive control signal. The controller **205** determines the second piezoelectric response of the piezoelectric electrode **115** in response to the first mechanical pressure **160** (step **325**). Next, the piezoelectric electrode **115** generates the second mechanical pressure **165** (step **330**). In some embodiments, the piezoelectric electrode **115** generates the second mechanical pressure **165** in response to receiving the piezoelectric control signal. The controller **205** determines the second capacitive response of the capacitive electrode **105** in response to the second mechanical pressure **165** (step **335**).

At step **340**, the controller **205** then determines the absolute sensitivity of the capacitive electrode **105**. In some embodiments, the controller **205** determines the absolute sensitivity of the capacitive electrode **105** based on the first capacitive response, the first piezoelectric response, and the second piezoelectric response. In some embodiments, the controller **205** determines the absolute sensitivity of the capacitive electrode **105** according to equation 5, described herein. At step **345**, the controller **205** determines the absolute sensitivity of the piezoelectric electrode **115**. In some embodiments, the controller **205** determines the absolute sensitivity of the piezoelectric electrode **115** based on the first capacitive response, the second capacitive response, and the first piezoelectric response. In some embodiments, the controller **205** determines the absolute sensitivity of the piezoelectric electrode **115** according to equation 7, described herein.

Thus, the disclosure provides, among other things, microphone systems and methods of determining absolute sensitivities on a MEMS microphone. Various features and advantages of the disclosure are set forth in the following claims.

What is claimed is:

1. A microphone system comprising:
a speaker configured to generate acoustic pressure;

a micro-electro-mechanical system (MEMS) microphone including
  a capacitive electrode configured to
    generate a first capacitive response based on the acoustic pressure, and
    generate a first mechanical pressure based on a capacitive control signal,
  a piezoelectric electrode coupled to the capacitive electrode and configured to
    generate a first piezoelectric response signal based on the acoustic pressure, and
    generate a second piezoelectric response signal based on the first mechanical pressure, and
  a backplate positioned parallel to the capacitive electrode; and
a controller configured to
  generate the capacitive control signal, and
  determine an absolute sensitivity of the capacitive electrode based on the first capacitive response, the first piezoelectric response signal, and the second piezoelectric response signal.

2. The microphone system according to claim **1**, wherein the controller is further configured to generate a piezoelectric control signal, and wherein the piezoelectric electrode is further configured to generate a second mechanical pressure based on the piezoelectric control signal.

3. The microphone system according to claim **2**, wherein the capacitive electrode is further configured to generate a second capacitive response based on the second mechanical pressure.

4. The microphone system according to claim **3**, wherein the controller is further configured to determine an absolute sensitivity of the piezoelectric electrode based at least in part on the first capacitive response, the second capacitive response, and the first piezoelectric response signal.

5. The microphone system according to claim **1**, wherein the controller is further configured to generate a speaker control signal, and wherein the speaker generates the acoustic pressure based on the speaker control signal.

6. The microphone system according to claim **1**, wherein the backplate is positioned on a first side of the capacitive electrode, wherein the piezoelectric electrode is positioned on a second side of the capacitive electrode, and wherein the second side of the capacitive electrode is opposite from the first side of the capacitive electrode.

7. A method of determining absolute sensitivities of a micro-electro-mechanical system (MEMS) microphone, the MEMS microphone including a capacitive electrode, a piezoelectric electrode coupled to the capacitive electrode, and a backplate, the method comprising:
generating acoustic pressure with a speaker;
generating a first capacitive response with the capacitive electrode based on the acoustic pressure;
generating a first piezoelectric response with the piezoelectric electrode based on the acoustic pressure;
generating a capacitive control signal with a controller;
generating a first mechanical pressure with the capacitive electrode based on the capacitive control signal;
generating a second piezoelectric response with the piezoelectric electrode based on the first mechanical pressure; and
determining an absolute sensitivity of the capacitive electrode with the controller based in part on the first capacitive response, the first piezoelectric response, and the second piezoelectric response.

8. The method according to claim **7**, wherein the method further comprises generating a piezoelectric control signal with the controller; and

generating a second mechanical pressure with the piezoelectric electrode based on the piezoelectric control signal.

9. The method according to claim **8**, wherein the method further comprises

generating a second capacitive response with the capacitive electrode based on the second mechanical pressure.

10. The method according to claim **9**, wherein the method comprises

determining an absolute sensitivity of the piezoelectric electrode with the controller based at least in part on the first capacitive response, the second capacitive response, and the first piezoelectric response.

11. The method according to claim **7**, wherein the method further comprises generating a speaker control signal with the controller, and wherein the speaker generates the acoustic pressure based on the speaker control signal.

12. A microphone system comprising:

a speaker configured to generate an acoustic pressure;

a micro-electro-mechanical system (MEMS) microphone including

a movable membrane having

a capacitive electrode configured to

generate a first capacitive response based on the acoustic pressure, and

generate a first mechanical pressure based on a capacitive control signal, and

a piezoelectric electrode configured to

generate a first piezoelectric response signal based on the acoustic pressure, and

generate a second piezoelectric response signal based on the first mechanical pressure, and

a backplate positioned on the capacitive electrode; and

a controller configured to

generate the capacitive control signal, and

determine an absolute sensitivity of the capacitive electrode based in part on the first capacitive response, the first piezoelectric response signal, and the second piezoelectric response signal.

13. The microphone system according to claim **12**, wherein the controller is further configured to generate a piezoelectric control signal, and wherein the piezoelectric electrode is further configured to generate a second mechanical pressure based on the piezoelectric control signal.

14. The microphone system according to claim **13**, wherein the capacitive electrode is further configured to generate a second capacitive response based on the second mechanical pressure.

15. The microphone system according to claim **14**, wherein the controller is further configured to determine an absolute sensitivity of the piezoelectric electrode based in part on the first capacitive response, the second capacitive response, and the first piezoelectric response signal.

16. The microphone system according to claim **12**, wherein the controller is further configured to generate a speaker control signal, and wherein the speaker generates the acoustic pressure based on the speaker control signal.

17. The microphone system according to claim **12**, wherein the backplate is positioned on a first side of the capacitive electrode, wherein the piezoelectric electrode is positioned on a second side of the capacitive electrode, and wherein the second side of the capacitive electrode is opposite from the first side of the capacitive electrode.

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